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IGNITION OF THE BEAM-PLASMA-DISCHARGE AND ITS DEPENDENCE ON ELE--ETC(U)
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A cold electron beam, propagating through a weakly ionized plasma will, under proper conditions, produce a modified beam-plasma state known as the Beam-Plasma-Discharge (BPD). As the subject of a continuing series of experiments in a large facility chamber it was previously determined that the BPD had an abrupt ignition threshold as the beam current (I_B) was increased at fixed beam energy. While a specific empirical relationship

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20. ABSTRACT *(Continued)*

was established among the controlling parameters of beam current, energy and length as well as ambient pressure and magnetic field, a dependence of the BPD on plasma density of the form $\omega_p \approx \omega_c$ was suggested. We have since conducted a survey of various beam-plasma conditions covering beam currents from 8 to 85 ma, beam energies from 0.8 to 2.0 keV and magnetic fields at 0.9 and 1.5 gauss. This survey includes full determinations of radial profiles of electron density for each of the selected conditions extending from a low-density pre-BPD state to a strong BPD condition. At BPD threshold N_e^{max} was determined and ω_p calculated with results that can be summarized by

$$\omega_p = \left(5.8 \begin{array}{l} +1.3 \\ -1.9 \end{array}\right) \omega_c$$

as the density dependent threshold condition for BPD. The experimental results are shown to compare favorably with a developing theoretical model that considers BPD to be triggered by electron plasma wave excitation of a beam-plasma instability.

CONTENTS

IGNITION OF THE BEAM-PLASMA-DISCHARGE AND ITS DEPENDENCE ON ELECTRON DENSITY

I. INTRODUCTION

A cold electron beam, propagating through a weakly ionized plasma will, under proper conditions, produce a modified beam-plasma state known as the Beam-Plasma-Discharge (BPD). This discharge state has received considerable attention in recent years as a result of increased interest in mechanisms for vehicle neutralization during spaceborne accelerator experiments (Bernstein, et al., 1980; Cambou, et al., 1978), enhanced beam-plasma ionization processes (Bernstein, et al., 1978), and in general single-particle or collective phenomena initiated by beam injection into neutral gas and charged-particle environments (Hess et al., 1971; Winckler, et al., 1975; Hendrickson and Winckler 1976; Cambou, et al., 1975; Monson and Kellogg 1978a; Szuszczewicz 1979; Jost et al., 1980). As the subject of a continuing series of experiments in a large vacuum chamber facility (Bernstein et al., 1978) it was determined that the BPD appears at a critical energetic-electron-beam current I_B^c, following the relationship

$$I_B^c \propto \frac{V_B^{1.5}}{B^{0.7} PL}, \qquad (1)$$

where V_B, B, P and L are the beam energy (voltage), the superimposed magnetic field, the ambient pressure and the beam length (gun aperture-to-collector distance), respectively.

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While the $I_B^c = I_B^c\,(V_B, B, P, L)$ relationship was established among the controlling system parameters, a dependence on plasma density was also expected, with early thoughts (Bernstein, et al., 1979) suggesting that $\omega_p = \omega_c$ satisfied ignition threshold criteria. We have conducted a survey of various beam-plasma conditions from 8 to 85 ma, beam energies from 0.8 to 2.0 keV and magnetic fields at 0.9 and 1.5 gauss. The survey included determination of radial profiles of electron density for each of the selected conditions extending from a low-density, pre-BPD state to a strong BPD condition. In summary, the results indicate that

$$\omega_p = (5.8\,{}^{+1.3}_{-1.9})\quad \omega_c \tag{2}$$

is the density-dependent threshold condition for BPD. The experimental details and analysis procedures that led to this result are presented below and compared with the predictions of a theoretical model which assumes that the BPD is triggered by electron plasma wave excitation of a beam-plasma instability.

II. EXPERIMENT CONFIGURATION AND RESULTS

The experiment was conducted in a 20 m diameter by 30 m high vacuum chamber facility at the NASA Johnson Space Flight Center. The configuration involved a pair of pulsed-plasma-probes mounted on a radial traversal mechanism positioned at approximately 8 m above the injection point of the beam.

Each of the probes provided simultaneous measurements of electron density N_e, temperature T_e, plasma potential V_∞, and density fluctuation power spectra δN_e ($\rightarrow P_n(k)$) with capability for the associated diagnostics under dynamic plasma conditions and under environmental conditions that could contaminate electrode surfaces (Holmes and Szuszczewicz, 1975, 1981; Szuszczewicz and Holmes 1975, 1976). Both of these conditions prevailed to various degrees.

A tungsten cathode gun was mounted near the chamber floor on a movable cart so that the beam could always be injected parallel to the magnetic field $\bar{B}$ and terminated on the 3 x 3 m target suspended about 20 m above the gun aperture. A combination of coil current and the Earth's magnetic field established the B-field at one of two levels, 0.9 and 1.5 gauss. The chamber was also equipped with a dipole-antenna/frequency-spectrum-analyzer system (Bernstein et al., 1979) which was used to determine BPD ignition from its characteristic plasma wave emissions. The dipole system was connected to a Tektronix spectrum analyzer with a frequency response from 200 kHz to 30 MHz. Because the high-frequency cut-off was not abrupt, frequencies up to 50 MHz could be detected readily.

In most cases the beam was injected into a neutral gas with no pre-beam plasma; however the experimental survey included two cases in which the chamber was filled with a pre-beam plasma created by a Kauffman-type argon ion thruster. In these cases the pre-beam plasma density was lower than the critical density at BPD ignition.

The survey included seven different conditions, each identified by pre-selected values for V_B, B, P and the existence or non-existence of a pre-beam plasma. For each condition a steady state value for I_B was set, a radial traversal was made and an electron density profile was recorded. A sample profile collected under pre-BPD conditions, is presented in Figure 1. The abscissa is time relative to the start of the radial traversal and the ordinate is relative electron density as determined by baseline electron-saturation currents collected by the E-probe. (The second probe in the two-probe configuration was defined as the I-probe because the associated baseline currents were collected in the ion-saturation portion of the probe's current-voltage characteristic (Holmes and *Szuszczewicz*, 1975, 1981).) At the start of each traversal the probe was at its outermost position relative to the center of the chamber. As time increased the probe was moved into and through the beam; at minimum radial distance from the chamber center, the traversal system was reversed, allowing a second measurement of the density profile as the probe moved back to its original outermost position. With this procedure the probe's minimum radial coordinate is identified by the symmetry point in the "double" profile.

Absolute electron densities were determined by standard P^3 analysis procedures summarized graphically in Figure 2. The technique provides a determination of relative electron

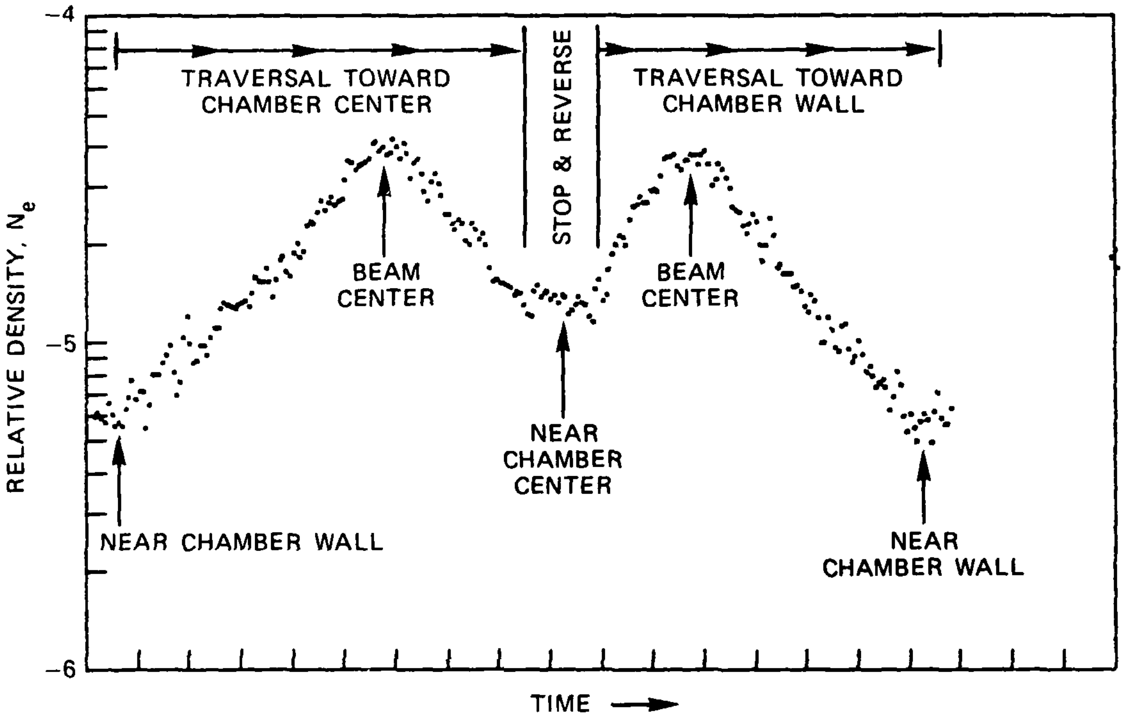

Fig. 1 — Radial profile of relative electron density under pre-BPD conditions. Run #57, (I_B, V_B, B) = (7 ma, 1.3 keV, 0.9G). The figure shows two cuts through the beam-plasma profile, as time increases from left-to-right the plasma density probe moves into and through the beam center, then reverses and passes through the beam a second time. The summetry verifies that beam-plasma conditions were stable during the execution of the radial traversal.

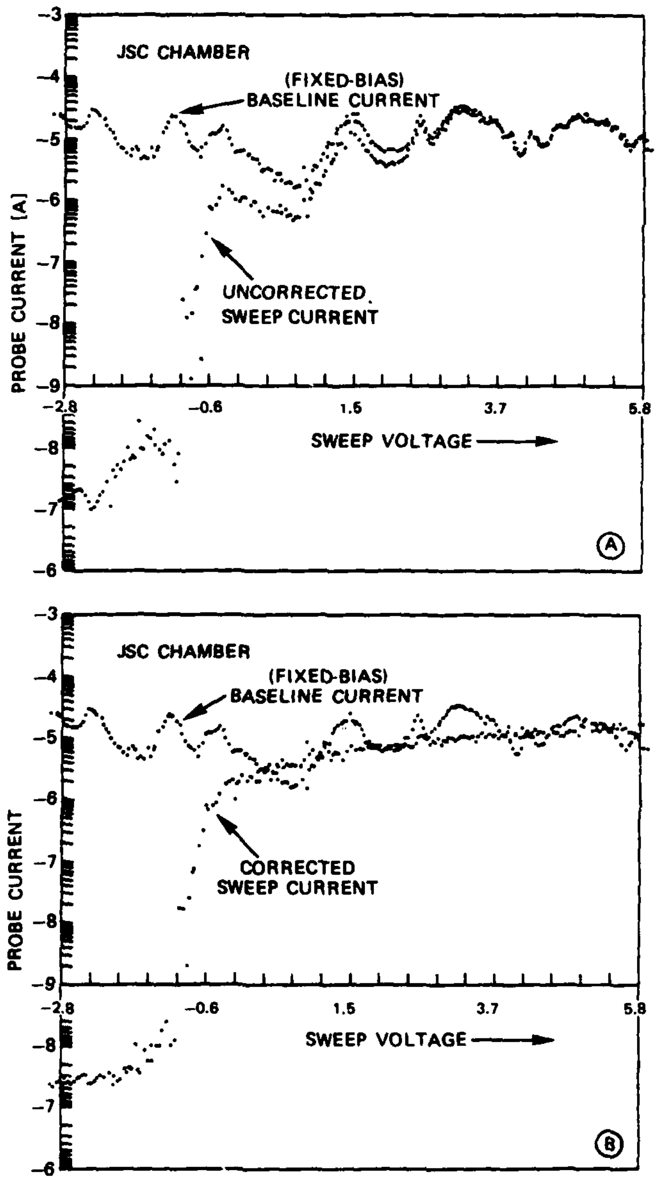

Fig. 2 — Sample of raw probe data (2A) showing the effects on density fluctuations (baseline *electron-saturation-currents*) on the probe's current-voltage characteristics (sweep currents). 2B shows the "corrected" characteristic.

density through the direct measurement of baseline electron-saturation-currents at a sample rate of 1 kHz. Simultaneously, the technique generates a "conventional" Langmuir probe characteristic. The relative density fluctuations (as indicated by the variations in the baseline current) are then unfolded from the raw, uncorrected probe characteristic (Fig. 2A) yielding a smooth, corrected curve (Fig. 2B) to which conventional N_e analysis procedures (Chen, 1965; Szuszczewicz and Holmes, 1977) are applied. This procedure was utilized for all beam-plasma conditions included in this investigation.

Relative electron density profile information and associated plasma wave signatures are presented in Figure 3 for $(V_B, B) = (1.3\ \mathrm{keV}, 0.9\mathrm{G})$. The transition from pre-, threshold- to solid-BPD can be seen as a function of beam current (I_B). The conditions at threshold and under BPD are summarized in Table 1 where the peak density N_e^{max} associated plasma frequency ω_p^{max}, and plasma-to-cyclotron frequency ratio ω_p^{max}/ω_c are also listed. The results can be summarized by

$$\omega_p = (5.8\ {}^{+1.3}_{-1.9})\ \omega_c$$

as the density-dependent threshold condition for the BPD.

III. DISCUSSION OF RESULTS

The experimentally derived threshold condition is reasonably consistent with the suggestion that BPD is triggered

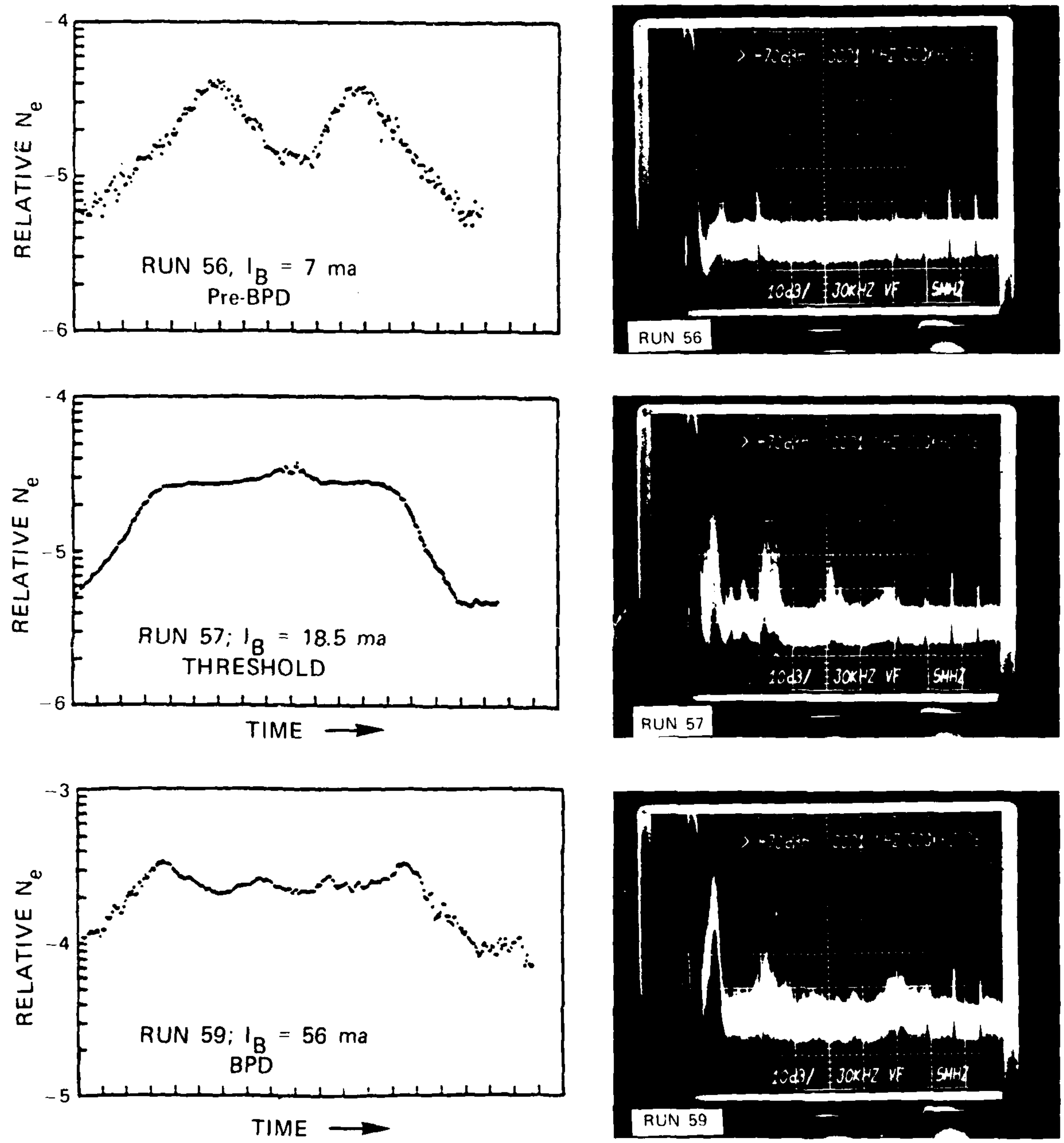

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Fig. 3 — Sequence of relative plasma density profiles and associated plasma wave signatures for increasing values of beam current I_B for a fixed condition (V_B, B) = 1.3 keV, 0.9G) encompassing rund 56 through 59 (pre-BPD through solid-BPD).

TABLE 1. ABBREVIATED SUMMARY OF BEAM-PLASMA SURVEY									
RUN #	BEAM-PLASMA STATE	ELECTRON GUN		CHAMBER CONDITION			N_e^{max}	f_c	f_p/f_c
		I_B (ma)	V_B(v)	B (g)	P (Torr)	THRUSTER			
40	THRESHOLD	37	1.9 (10^3)	0.9	0.7-1.5 $(10\ ^5)$	ON	3.6 (10^6)	2 5 (10^6)	6.92
41	BPD	47	1.9 (10^3)	0.9	0.7-1.5 $(10\ ^5)$	ON	5.6 (10^6)	2.5 (10^6)	8.60
48	THRESHOLD	34	1.9 (10^3)	0.9	0.7-1.5 $(10\ ^5)$	OFF	3.3 (10^6)	2.5 (10^6)	6.6
49	BPD	45	1.9 (10^3)	0.9	0.7-1.5 $(10\ ^5)$	OFF	5.0 (10^6)	2.5 (10^6)	8 12
57	THRESHOLD	18.5	1.3 (10^3)	0.9	0.7-1.5 $(10\ ^5)$	OFF	1.5 (10^6)	2.5 (10^6)	4.45
58	BPD	28	1.3 (10^3)	0.9	0.7-1.5 $(10\ ^5)$	OFF	4.5 (10^6)	2.5 (10^6)	7 71
63	THRESHOLD	7.8	800	0.9	0.84-1.5 $(10\ ^5)$	OFF	0.98 (10^6)	2.5 (10^6)	3.7
64	BPD	9.9	800	0.9	0.84-1.5 $(10\ ^5)$	OFF	2.6 (10^6)	2.5 (10^6)	5.9
69	THRESHOLD	6.2	800	0.9	0.7 $(10\ ^5)$	ON	3.8 (10^6)	2.5 (10^6)	7.08
70	BPD	7.8	800	0.9	0.7 $(10\ ^5)$	ON	3.6 (10^6)	2.5 (10^6)	6.89
81	THRESHOLD	20	2.0 (10^3)	1.5	0.6-1.2 $(10\ ^5)$	OFF	7.0 (10^6)	3.7 (10^6)	6.65
82	BPD	30 5	2.0 (10^3)	1 5	0.6-1.2 $(10\ ^5)$	OFF	1.8 (10^7)	3.7 (10^6)	10.7
86	THRESHOLD	12	1 3 (10^3)	1.5	0.6-1.2 $(10\ ^5)$	OFF	3 9 (10^6)	3 7 (10^6)	4.96
87	BPD	18	1.3 (10^3)	1 5	0.6-1.2 $(10\ ^5)$	OFF	1 1 (10^7)	3.7 (10^6)	8.34

by the onset of a beam plasma instability excited by electron plasma waves (Rowland et al., 1981; Papadopoulos, private communication, 1981). Qualitatively the threshold process can be described as follows:

(i) As an electron beam linearly interacts with a neutral gas, it collisionally produces a plasma with a density that varies directly with the magnitude of the beam current for a fixed beam energy.

(ii) As the beam current is increased further, a two-stream instability develops in which the electric fields of the excited waves "heat" the electrons to energies comparable to the ionization energy of the neutral species. The "heated" electrons create an enhanced *ionization process* which results in an avalanche breakdown during the BPD.

Detailed theoretical considerations (Rowland et al., 1981) involving finite beam-plasma geometries suggest that the threshold for BPD ignition corresponds to the onset of convective instability. Quantitatively that threshold takes the form

$$\omega_p \geq 1.4\ v_b/r_o\ \sqrt{\ln(R/r)} \qquad (3)$$

where r_o and v_b are the beam radius and velocity, and R is the radius of the plasma with which the beam interacts. For the experimental conditions, r_o is taken to be controlled by the gun half-divergence angle θ, the beam velocity v_b and the superimposed magnetic field. We therefore write

$$r_o = (v_b \sin\theta)/\omega_c \,, \tag{4}$$

allowing the theoretically predicted threshold condition to be rewritten as

$$\frac{\omega_p}{\omega_c} \geq \frac{1.4\ (1.2)}{\sin\theta} \tag{5}$$

where $1.2 = 1/\sqrt{\ln (R/r_o)}$ has been selected as the experimental average. Equation (5) suggests that the ω_p/ω_c threshold condition is a constant, independent of B itself, and controlled only by the beam cross section through the half-divergence angle θ. Qualitatively this is in agreement with the experimental results. For a quantitative comparison, we estimate θ in the range, $5^o \leq \theta \leq 10^o$, yielding

$$9.6 \leq \omega_p/\omega_c \leq 19.3 \tag{6}$$

as the spread in values theoretically predicted for BPD ignition. This result, while sensitive to the uncertainties in θ and R/r_o (e.g., electrostatic forces and beam spreading have not been included), is taken to be in reasonably good agreement with the experimentally derived conditions (2). Inclusion of beam spreading would effectively increase θ (Linson and Papadopoulos, 1981) and improve the agreement, providing ever stronger arguments which deny the original notion that $\omega_p = \omega_c$ described BPD threshold

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